A look at how the NASA Pandora Project is being used in support of the Canada–United States Air Quality Agreement.
Evaluating progress on transboundary air issues, in support of the Canada–United States Air Quality Agreement, requires scientifically credible methods that can span the 8,900-km border. Progress has been tracked by a combination of in-situ deposition sampling, source monitoring (e.g., Continuous Emission Monitoring System), and atmospheric modeling. There is recognition that low-earth orbit UV/visible measurements and soon-to-be launched geostationary-orbit UV/Vis spectrometers can be an important tool for monitoring air pollutant abundance and transport. To enhance the integrity of using satellite data products for interpreting impacts on surface air quality, there is a need to develop an integrated air quality monitoring and satellite validation network.

The technology and science underpinning the ability to retrieve trace gas column abundance from satellite-based spectrometers have matured over the past several decades, resulting in higher resolution data (e.g. GOME-2 40 x 40 km resolution, OMI with nominal 13 x 24-km resolution vs. Sentinel 5P TROPOMI with nominal 7 x 7-km resolution; see Figure 1).

While satellites in low-earth orbit provide once-a-day observations of an area of interest at best, remotely sensed air quality research and monitoring is on the cusp of a new era with the launch of a series of geostationary air quality instruments from 2020 to 2023: Korea–GEMS (Geostationary Environment Monitoring Spectrometer), NASA–TEMPO (Tropospheric Emissions: Monitoring Pollution), and European Space Agency (ESA) Sentinel-4.

As geostationary weather satellites have revolutionized mesoscale weather forecasting, this next generation of geostationary air quality instruments has the potential to revolutionize how air quality and pollutant transport is monitored. However, with these advancements, a new set of challenges associated with validation of their hourly measurements and data products arises. Monitoring air quality from space is a strategic research area within both the United States and Canada, and is a focus area for technical cooperation under the agreement. While there have been efforts to evaluate and validate satellite-based trace gas data products, routine and

![Figure 1. NO2 measured by TROPOMI (a) and OMI (b) on April 9, 2018, over the surface mines of the Alberta Oil Sands Region (w/NW winds). Averages (March–May, 2018) with an averaging radius of 5 km and 16 km were used for TROPOMI (c) and OMI (d), respectively. The black line traces the borders of the individual mining operations.17]
systematic validation of the geophysical parameters uncertainty and representativeness in space and time on a large scale is rare, with cost and technology being the main limiting factors.

**Pandora Ground-Based Spectrometer**

In 2005, NASA initiated an effort at Goddard Space Flight Center (GFSC) to address the gap in validation measurements through the development of cost-effective, easy-to-deploy, ground-based spectrometer called Pandora. Pandora is a compact, modestly-priced sun/sky/lunar passive UV/Visible grating spectrometer system. Over the past decade, the NASA Pandora Project together with the ESA Pandonia project, have endeavored to mature and refine the Pandora spectrometer system.

When the spectrometer and head assembly are carefully calibrated, Pandora provides high-quality spectrally resolved direct sun/lunar or sky scan radiance measurements in the UV and visible wavelengths. The Pandora radiance measurements combined with trace gas spectral fitting routines, and (in the case of sky-scan measurements) radiative transfer modeling provide real-time data of key air quality relevant pollutants, which can be compared to similar measurements from satellites. These observations include total column ozone (O$_3$), nitrogen dioxide (NO$_2$), formaldehyde (HCHO), sulfur dioxide (SO$_2$) and bromine oxide (BrO). Figure 2 shows the various components of the Pandora system, and their installation in different configurations, while Table 1 provides technical details on the components and measurement quality.

Environment and Climate Change Canada (ECCC) and the U.S. Environmental Protection Agency (EPA) have partnered with NASA and ESA in the deployment of Pandora instruments across North America. While the spatial distribution of Pandora instruments in the field is not explicitly guided by issues of transboundary transport of air pollutants, data provided from the confederated network will be used to validate satellite data products of direct relevance to transboundary transport.

**Pandora Network**

Within the United States and Canada, measurements from Pandora instruments have demonstrated a new observational perspective of air quality. The O$_3$ and NO$_2$ products have been rigorously investigated over the course of a decade during a series of intensive field campaigns and also at long-term monitoring sites.$^3$-$^8$

**The United States**

In the United States, NASA’s Deriving Information on Surface conditions from COlmumn and VERTically resolved observations relevant to Air Quality (DISCOVER-AQ) mission$^9$ involved the deployment of Pandora spectrometers at local air quality sites in each study domain: Baltimore, MD (2011), San Joaquin Valley, CA (2013), Houston, TX (2013), and Denver, CO (2014). The local air quality sites, many of them either part of EPA’s State and Local Air Monitoring Stations (SLAMS) or Photochemical Assessment Monitoring Station (PAMS) networks, served as measurement anchor points for the coordinated 3D sampling strategy (airborne spirals, ground-, and aircraft-based remote sensing).

DISCOVER-AQ results highlighted both the ability and the importance of routinely monitoring factors affecting the 3D distribution of NO$_2$. NO$_2$ is a precursor of tropospheric O$_3$ production. Understanding its 3D distribution is thus important for understanding patterns of O$_3$ production, exposure, and transport.

Figure 3 demonstrates the power of adding Pandora (i.e., total NO$_2$ vertical column measurements) to a conventional air monitoring station for understanding the vertical distribution of NO$_2$. Pandora does not differentiate tropospheric NO$_2$ from stratospheric NO$_2$ columns, so we must make two assumptions. First, we assume that a stratospheric contribution to the total column is spatially uniform over all of Denver area and slowly increases through the day from $3.1 \times 10^{15}$ molecule cm$^{-2}$ at 6:00 a.m. MST to $4.4 \times 10^{15}$ molecule cm$^{-2}$.

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**Figure 2.** (a) environmental enclosure housing instrument electronics (left), spectrometer on thermal electric cooler (right), computer (not shown), (b) sensor head with camera and enhanced sun tracker, (c) another configuration with sensor head installed on the roof of a trailer, and the spectrometer and computer located inside the trailer.
at 6:00 p.m. MST, consistent with previous climatological measurements. The second assumption is that the entire tropospheric NO₂ column is located within the boundary layer and that the boundary layer is well mixed, a reasonable approximation in urban environments near sources given the relatively short lifetime of NO₂ in the atmosphere.

With these assumptions, we are able to infer that the decrease of NO₂ surface concentration after 11:00 a.m. MST, as shown in Figure 3 relative to the Pandora NO₂ column reflects growth in the boundary layer mixing NO₂ higher in the atmosphere, or over a greater volume. This inference is supported by the temporal increase in the vertical extent of aerosol backscatter and increasing mixed layer height while the total NO₂ column remains relatively constant between 11:00 a.m. and 1:00 p.m. MST. The significance being that this behavior is not possible to observe with surface in-situ sensors alone.

Additional field campaigns, such as the 2016 NASA/NIER KORUS–AQ study: An International Cooperative Air Quality Field Study in Korea (https://www-air.larc.nasa.gov/missions/korus-aq/), the 2017 NASA/EPA Lake Michigan Ozone Study (https://www.ladco.org/technical/projects/lmos-2017/), the 2017 and 2018 Ozone Water Land Environmental Transition Study (OWLETS 1 & 2; http://pubs.awma.org/flip/EM-Aug-2016/crawford.pdf) and 2018 Long Island Sound Tropospheric Ozone Study (http://www.nescaum.org/documents/listos), have effectively served as opportunities to continue the evaluation of the operational performance of the Pandora systems and to characterize column NO₂ diurnal patterns.

In 2015, EPA finalized changes to the PAMS Network, which included the addition of an Enhanced Monitoring Plan (EMP) for certain regions of the United States with persistent O₃ non-attainment issues. Informed by the use of Pandora spectrometers in multiple field campaigns to monitor column NO₂, recent EMP guidance provides the opportunity for state and local agencies to work with EPA and NASA to incorporate Pandora spectrometers into select monitoring sites as a component of the EMP. Under the new EMP monitoring requirements, Pandora column NO₂ combined with mixed-layer height measurements and surface in-situ measurements of true NO₂ will better aid in the characterization of NO₂ and allow for a direct comparison with satellite-based NO₂ column measurements.

Canada

In Canada, ECCC’s Pandora program is focused primarily on long-term monitoring. One of the first sites is Fort McKay (57.184°N, 111.64°W) in the Canadian oil sands region, where Pandora measurements began on August 15, 2013. Located in the province of Alberta, the oil sands region contains vast deposits of bitumen–oil mixed with sand, clay, and water. Environmental and health concerns associated with the oil sands operations, including air quality and acid deposition, are well known. The SO₂ emission sources in the oil sands region are among the largest in Canada, while NO₂ emissions are comparable to those from a small town. Due to the large area of the oil sands operations, satellite measurements are an appealing approach for air pollution monitoring in this region. Pandora was deployed to provide total column SO₂ measurements and validation of satellite NO₂ observations. Pandora SO₂ measurements compared with in-situ data during the “pollution events” at Fort McKay (see Figure 4) demonstrate Pandora’s capability for air quality monitoring.

ECCC deployed Pandora instruments at three sites in or north of the Greater Toronto Area between 2013 and 2018 to validate TROPOMI measurements at high spatial resolution. In 2018, an additional Pandora instrument was installed near Edmonton, AB, to study urban pollution, as well as

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### Table 1. Overview of Pandora Spectrometer.

- System developed at NASA Goddard with a focus on satellite validation.
- Ground-based direct sun/moon and sky scanning remote sensing for air quality and atmospheric composition
  - 1-Spectrometer (1S) unit – spectral range 270–530 nm, resolution 0.6 nm
  - 2-Spectrometer (2S) unit: spectral range 400–900 nm, resolution 1 nm
- Initial measurement is a slant column
- NRT Standard Operational Products at high frequency (~ 2 mins): Total Column Ozone (+/-15 Dobson unit, ~5%); Total Column NO₂ (+/-0.05 Dobson unit, ~10%)
- Research products: HCHO, BrO, profile and near-surface NO₂, tropospheric and near-surface O₃.
- Two main parts to instrument: (1) sensor head and (2) spectrometer, thermoelectric cooler, electronics, computer contained with environmental housing case 23x16x39 inches or 8-inch rack mounted enclosure.
pollution from large coal-burning power plants located in the area. To withstand harsh winter conditions, all Canadian installations are configured with the sensor head placed outside, while the spectrometer and computer are indoors in a temperature-controlled environment.

Although scientific analyses have been published on both \( \text{SO}_2 \) and \( \text{HCHO} \), these products and their associated algorithms are still undergoing review and require verification to ensure their integrity before becoming a standard data product. These focused studies, along with others in Europe, have provided opportunities to evaluate instrument operations and performance, which have resulted in engineering and software changes to increase operational reliability and long-term stability of the Pandora system.

The current distribution of Pandora instruments deployed in North America is depicted in Figure 5, with ECCC, NASA, and EPA instruments color coded separately. With the launch of TROPOMI (October 2017) and the future launch of the geostationary TEMPO instrument circa 2021, the Canada–U.S. Air Quality Agreement is providing a mechanism for scientific cooperation between ECCC, NASA and EPA to define a coordinated satellite validation strategy and measurement instrument suites at long-term sites, with these sites also being within a larger global network.

**The Pandonia Global Network**

NASA and ESA are collaborating to coordinate and facilitate an expanding global network of standardized, calibrated Pandora instruments focused on air quality and atmospheric
The Pandora Global Network (PGN) endeavors to ensure systematic processing and dissemination of the data to the greater global community in support of in-situ and remotely sensed air quality monitoring. A major joint objective is to support the validation and verification of more than a dozen low-earth orbit and geostationary orbit based UV-visible sensors, most notably Sentinel 5P, TEMPO, GEMS, and Sentinel 4.

PGN participants are primarily comprised of governmental and academic researchers and technicians. The launch of the PGN in mid-2019 represents a programmatic shift by NASA and ESA toward establishing long-term fixed locations that are focused on providing long-term quality observations of total column and vertically resolved concentrations of a range of trace gases. PGN provides real-time, standardized, calibrated, and verified QA/QC air quality data. PGN also seeks to coordinate and implement network standards regarding common algorithms and data processing, instrument operating routines, quality control, real-time data processing, and data archiving.

**Conclusion**

The scientific cooperation and partnership between ECCC and NASA/EPA on the Pandora Spectrometer System will be beneficial to both countries with specific areas of collaboration focused on instrument development, standardization of deployment and operations, shared data processing techniques, and combined analysis of results. The cooperation on Pandora as a new routine and systematic monitoring

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**Figure 4.** \( \text{SO}_2 \) VCD (DU) measured by Pandora spectrometer (red dots) at Fort McKay and calculated from integrated aircraft \( \text{SO}_2 \) profile measurements (blue dots), as well as in-situ \( \text{SO}_2 \) concentration in parts per billion by volume (ppbv; green line).

**Figure 5.** The current distribution of deployed Pandora systems in Canada and the United States. Each site is color-coded to correspond to the agency owner of the Pandora with total numbers deployed indicated in the legend.
approach is expected to assist in providing an improved characterization and validation of satellite data, leading to greater use of satellite data to monitor and assess emissions and transport of air pollution over the vast areas that contribute to transboundary pollution. In addition, the PGN is expected to play a critical role through implementation of standards across the network, which will assist ECCC and EPA on the development of a common measurement platform.

References